63-4-1

ASD-TDR-63-230

CATALOGED BY DDC
AS AD No. 407689

Correlation of Wind Tunnel Blockage Data

Paul A. Czysz

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-230
April 1963

Directorate of Engineering Test
Deputy for Test and Support
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 142601, Task No. 1426

ASD-TDR-63-230

Correlation of Wind Tunnel Blockage Data

Paul A. Czysz

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-230
April 1963

Directorate of Engineering Test
Deputy for Test and Support
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 142601, Task No. 1426

NOTICES

31-788T, 300, 6-14-63

FOREWORD

This report was prepared by Paul Czysz of the Hypersonic Gasdynamics Branch, Aerodynamics Division, Directorate of Engineering Test, Deputy for Test and Support, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. It describes an experimental program to investigate the blockage limits for the Mach 4 High Temperature, Hypersonic Gasdynamics Facility. This work covers the period from September 1961 through May 1962.

This program was performed under the continuous Task Number 142601, Hypersonic Tunnel Studies of Project 1426, Experimental Simulation of Flight Mechanics.

ABSTRACT

An experimental investigation of the test section flow blockage characteristics was conducted at Mach 4 in the High Temperature Hypersonic Gasdynamics Facility.

The models utilized in this program were pointed and blunted cones from 5-degree half angle to 90-degree half angle, flat plates, delta winged shapes, and hemispherical models, some of which were run up to 40-degree angle of attack. Comparison of the data with other facilities resulted in a correlation of the maximum model size compared to the potential flow core size with Mach number and drag coefficient for both open and closed test section configurations for Mach numbers from 1.5 to > 10.

This technical documentary report has been reviewed and is approved.

Webster W. Plourd

WEBSTER W. PLOURD
Colonel, USAF
Asst Deputy for Test and Support

COORDINATION FOR ASD TECHNICAL DOCUMENTARY REPORT 63-230

PREPARED BY:

Paul Czysz

PAUL CZYSZ
Acting Chief, Hypersonic
Gasdynamics Branch
Aerodynamics Division

CONCURRED IN:

for Carl E Reichert

WILLIAM J. DuBOIS
Director, Engineering Test
Deputy for Test and Support

CONCURRED IN:

Hugh S. Lippman

HUGH S. LIPPMAN
Technical Director
Deputy for Test and Support

APPROVED BY:

Webster W Plourd

WEBSTER W. PLOURD
Colonel, USAF
Asst Deputy for Test and Support

TABLE OF CONTENTS

LIST OF FIGURES

SYMBOLS

A	nominal geometric test section area, (in.^{2})
ΔA	area of model normal to the flow, (in.^{2})
A_{core}	area of the potential flow core, $(R_e - \delta^*)^2 \pi$, (in.^{2})
A^*	nozzle throat area, (in.^{2})
A_1^*	throat area for primary ejector nozzle, (in.^{2})
A_3	area of ejector mixing tube, (in.^{2})
$\frac{\Delta A}{A_{core}}$	ratio of area of model normal to the flow to the area of the potential flow core
$\left(\frac{\Delta A}{A}\right)_T$	one dimensional, normal shock theory, $1-\left(\frac{P_0}{P_0'}\right)\left(\frac{A^*}{A}\right)$
C_D	drag coefficient of model
d	model diameter, (in.)
D_3	ejector mixing tube diameter, (in.)
M	Mach number
P_0	facility stagnation pressure, (psia)
P_0'	stagnation behind normal shock, (psia)
P_{01}	primary stagnation air pressure, ejector, (psia)
P_{02}	secondary stagnation air pressure, ejector, (psia)
P_c	plenum pressure (psia)
P_∞	free stream static pressure (psia)
R	body radius, (in.)
R_e	radius of nozzle at the exit (in.)
T_0	facility stagnation temperature, (°R)
T_{01}	primary air stagnation temperature, ejector (°R)
T_{02}	secondary air stagnation temperature, ejector (°R)

SYMBOLS (CONT'D)

δ^*	displacement boundary layer thickness, (in.)
Δ	distance from the nozzle exit to the nose of the model (in.) positive downstream
θ_s	shock wave angle, (degrees)
μ	$\sin^{-1}\left(\frac{1}{M}\right)$, Mach line, (degrees)
σ	cone half angle, (degrees)
λ	the number of times the pressure ratio across the facility is greater than normal shock

SUBSCRIPTS

p	perfect gas
tp	thermally perfect, calorically imperfect gas

INTRODUCTION

The starting process associated with a model and model support system in a supersonic wind tunnel is very complex, and cannot be adequately represented by a single simple expression such as one-dimensional normal shock theory. Further discrepancies are caused by small, seemingly insignificant items not directly associated with the model, which substantially affect the maximum model size which will run. Rather than attempting to predict model blockage to a few percent for a particular facility, a general guide which would give approximately the area in which blockage would occur for most supersonic facilities seems to be reasonable. Since the experience of this organization shows that models operating near the upper limits of model size will not produce valid data, no realistic program would employ the use of models close to maximum size. Efforts were directed toward investigating the blockage characteristics of the High Temperature Facility, and correlating this data, and that from other investigators into a general guide.

TEST EQUIPMENT

This program was accomplished in the ASD High Temperature, Hypersonic Gasdynamics Facility (HTF). This facility had installed a Mach 4 nozzle with an exit diameter of 5 inches, and an open test section 10.5 inches long. The facility was equipped with a rotary model support capable of sequentially injecting six models into the test section. A general arrangement of the facility is shown in figure 9 and a complete description of the facility and its operation can be found in reference 6.

There are essential differences in the type wind tunnel used in this study and those used in the references; figure 1 shows schematically these differences. The HTF was an open test section configuration enclosed by a plenum tank so that the ambient pressure was approximately equal to the static pressure at the nozzle exit; in order to accomodate plenum leakage and diffuser spillage the plenum tank was pumped by an air to air ejector. The maximum quantity of air pumped by this ejector was no more than 3 percent of the nozzle weight flow and it added considerably to the size of the model which could be run in the test section. With a good diffuser on the facility, the ejector was essentially compensating for plenum leaks; with a poor diffuser it also had to handle air spilled by the diffuser. The final configuration of the ejector and diffuser were as follows:

EJECTOR

Primary Nozzle	$M = 4.45$
Primary pressure	500 psig
Primary temperature	500°R
Primary weight flow	1.15 lb/sec
Secondary pressure Secondary weight flow	Figure 8
Secondary temperature	700°R

Manuscript released by the author March 1963 for publication as an ASD Technical Documentary Report.

DIFFUSER

Entrance diameter	6.0 inches
Throat diameter	4.85 inches
Throat length	30 inches
Entrance cone	7 1/2-degree half angle

The diffuser had a sharp leading edge on the entrance cone approximately .01 inch radius and was completely water cooled.

The operational envelope with this system is shown in figure 2. The plenum chamber pressure with no model in the flow and ejector not operating, was approximately 1.20 P_{∞}. The data presented in figure 7 of reference 8 was for the same diffuser but with a Mach 2 primary nozzle on the ejector.

MODELS

The models consisted of a set of cones and hemispheres from 0.75-inch diameter to a 2-inch diameter in increments of 0.25 inch. The cones had half angles of 5, 10, 15, 20, 30, 40, 50, and 90 degrees. Models from reference 7 through reference 12 were also utilized for this program. These included:

1. Blunted 15-degree half angle cone up to a 40-degree angle of attack.

2. Flat plate up to an 18-degree angle of attack

3. Delta winged vehicles up to an 18-degree angle of attack

4. Cone-Cylinder-Flare models up to a 15-degree angle of attack.

THEORY

The establishment of the flow in a supersonic wind tunnel is generally described by one-dimensional theory with the total entropy rise across the system equal to that of a normal shock. The maximum model size which will start is then given by

$$\frac{\Delta A}{A_{core}} = 1 - \frac{P_o}{P_o'} \left[\frac{A}{A_{core}}\right]$$

In practice the actual entropy rise cannot be represented by the increase through one shock and, in fact, many of the factors significantly influencing the model size are not at all related to the model.

If reference 14 is used, the effect of caloric imperfection can be estimated for one dimensional theory. After rearranging a few terms we can write

$$\frac{\left[1 - \frac{\Delta A}{A_{core}}\right]_{tp}}{\left[1 - \frac{\Delta A}{A_{core}}\right]_{p}} = \frac{\left[P_o'/P_o\right]_p}{\left[P_o'/P_o\right]_{tp}} \; \frac{\left[A/A^*\right]_p}{\left[A/A^*\right]_{tp}} = K_1 \qquad (1)$$

then

$$\frac{\left[\frac{\Delta A}{A_{core}}\right]_{tp}}{\left[\frac{\Delta A}{A_{core}}\right]_{p}} = \frac{1 - K_1}{\left[\frac{\Delta A}{A_{core}}\right]_{p}} + K_1 \qquad (2)$$

These two equations are plotted in figure 3.

This trend was exhibited in the HTF in that generally slightly larger angles of attack and models could be run at the higher operating temperatures. The blockage studies were run at approximately 4000°R, references 8 through 12 for stagnation temperature from 4700°R to 2800°R.

For the open test section there are factors other than the magnitude of the model cross sectional area which limits model size. One of these is the impingement of the weak waves from the nozzle exit on the model base (figure 4). This limitation restricts the size of slender cones which according to experiments in Closed Test Section Facilities should be equal to, or greater than the permissible sizes predicted by one dimensional theory.

Beginning with two equations, one for the radius of a cone, the other the location of a Mach wave off the nozzle, we have

$$Y = (Re - \delta^*) \mp x \tan \mu \qquad (3)$$

$$R = (X - \Delta) \tan \sigma \qquad (4)$$

For x, only downstream of the nozzle exit, the interaction of the Mach wave and the base of the body occur when

$$Y = R$$

using the relation,

$$\left[\frac{R_e - \delta^*}{R}\right] = \left[\frac{\Delta A}{A_{core}}\right]^{-1/2}$$

and

$$D_p = 2(R_e - \delta^*)$$

we have after some algebraic manipulation

$$\left[\frac{\Delta A}{A_{core}}\right] = \left[\frac{1 - \left(\frac{2\Delta}{D_p}\right)\tan\mu}{1 + \frac{\tan\mu}{\tan\sigma}}\right] \tag{5}$$

figure 4 presents equation 5 for $\Delta = 0$. The maximum model size is quite limited for pointed low angle cones, and is analogous to long, three dimensional models which are to be pitched to angle of attack. If the nose of the model is downstream of the nozzle exit, the angle of attack can be severely limited.

RESULTS AND DISCUSSION

The results from this study and references 2 through 5 are presented in figure 5 as a function of nose drag coefficient. There is good agreement among the various investigations for drag coefficients less than about 0.7, greater than this, there is considerable difference in the maximum model size that would start under similar conditions. The theory for open test section agrees favorably with the data for Mach Number 4 taken in the HTF and seems to predict reasonable maximum values. Lines of constant Mach number were faired through the data points to represent approximately marginal starting conditions. Since the experience with the HTF has been that heat transfer, and pressure distribution data obtained at near maximum blockage limits is rather poor, these limits will give a reasonable idea of the maximum model size that could run, but in general would not be actually used in a program.

As stated in reference 2, there are many factors other than the model size affecting blockage. Similar experience as reported by Schueler, have repeatedly occurred in the HTF and emphasis on considering the nozzle-diffuser-model model support system cannot be placed too strongly.

In figure 6 and figure 7 the correlated data is presented as permissible model size as a function of Mach number with C_D as a parameter for closed and open test sections, respectively.

Figure 10 shows typical Schlieren photographs of the various models used to obtain the data for this report.

CONCLUSIONS

Model blockage results can be reasonably well correlated as a function of Mach number and drag coefficient for most shapes even at angles of attack up to 40 degrees.

Sphere and Disk models show the most scatter and although good correlation is not evident, the suggested permissible model size for a $0.8 < C_D < 2.0$ is not unreasonable considering the experimental results.

The theory for predicting the maximum model size for slender bodies in an open test section is reasonably good. Therefore, the approximate maximum permissible models which will start for both open and closed test section facilities can be established.

REFERENCES

1. Crook, R. T., Operating Characteristics, Investigation; High Temperature, Hypersonic Gasdynamics Facility, Engineering Test Report ASTEA 61-24, 7 Dec 61.

2. Schueler, C. J., An Investigation of the Model Blockage for Wind Tunnels at Mach Numbers 1.5 to 19.5, AEDC TN 59-165, Feb 1960.

3. Draper, A. C., Redefinition of the Limiting Concept for Supersonic Wind Tunnel Blockage, WADC TN 58-186, June 1958, AD 155 692.

4. Dayman, Bain Jr., Prediction of Blocking in the Supersonic Wind Tunnel During an Attempted Start, Jet Propulsion Laboratory External Publication No. 669, July 1959.

5. DeLeo, R. V. and Rose, R. E., An Experimental Investigation of the Use of Supersonic Driving Jets for Ejector Pumps, WADC TR 57-357, December 1958, AD 206 662.

6. Milling, Robert W. Captain, USAF, The High Temperature Hypersonic Gasdynamics Facility, ASD TN 61-107, AD 266 728.

7. George C. Marshall Space Flight Center publication, Aerodynamic Characteristics of Spherically Blunted Cones at Mach 0.5 to 5, MPT-AERO-61-38, May 1961.

8. Czysz, P. A., Investigation of Ablation Bodies in the High Temperature Hypersonic Gasdynamics Facility, ASD Engineering Test Report ASTEA 62-2R, February 1962.

9. Czysz, P. A., Hypersonic Flow Photographs, ASD Engineering Test Report, ASTEA 61-6R, January 1962.

10. Everling, P. C., Aerodynamic Heating of a Blunted Cone With a Gas Ejecting Spike, ASD Engineering Test Report ASTEA 62-14R, August 1962.

11. Smith, R. R., Investigation of Flow Variables on a Series of Rearward Facing Stepped Flat Plates, ASD-TDR-63-131, February 1963.

12. Czysz, P. A., Hemisphere-Cylinder Heat Transfer Study ASD-TDR-63-404, February 1963.

13. Crook, R. T., Calibration of the HTF 5-Inch Conical Nozzle, ASD Engineering Test Report, ASTEA 62-4R, April 1962.

14. NACA Report 1135, Equations, Tables, and Charts for Compressible Flow, Ames Research Staff, 1953.

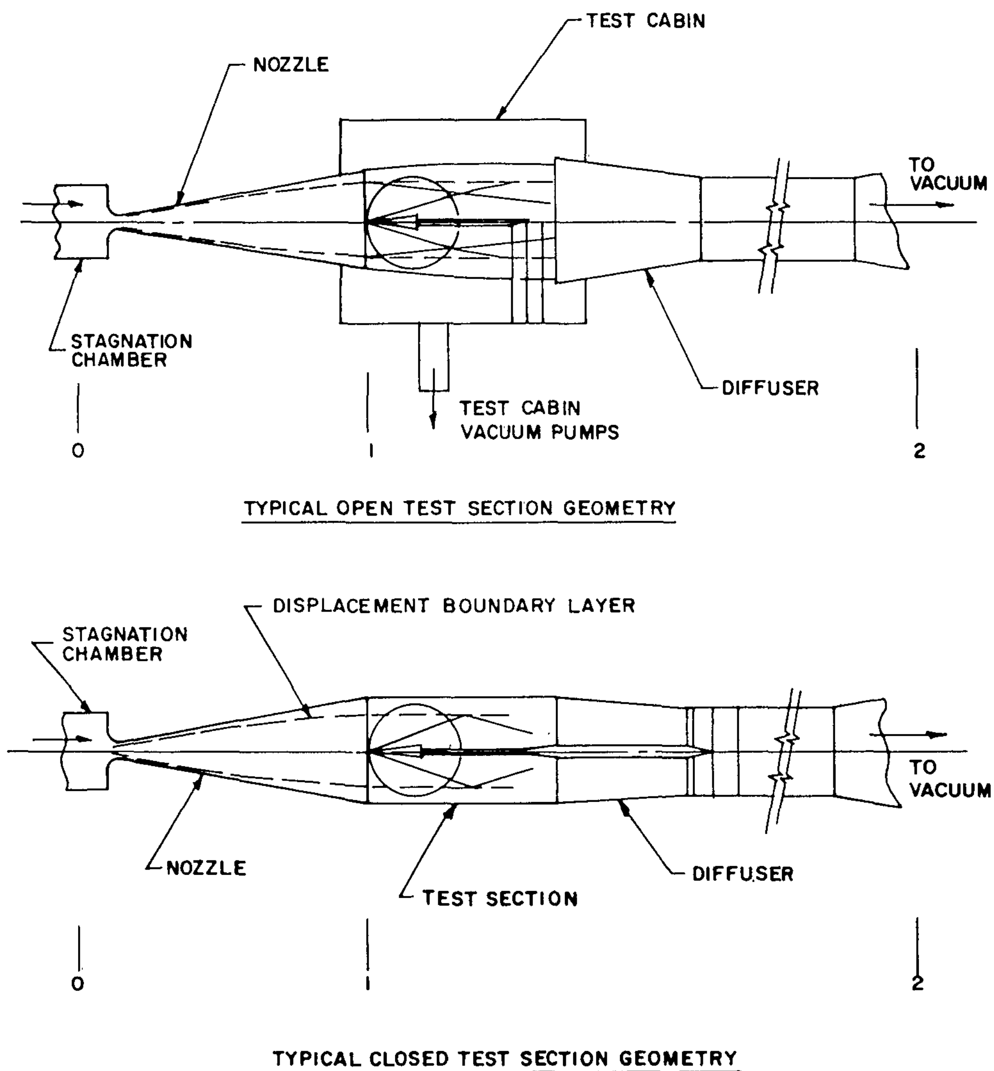


Figure 1. Schematic Representation of Closed and Open Test Section Facilities

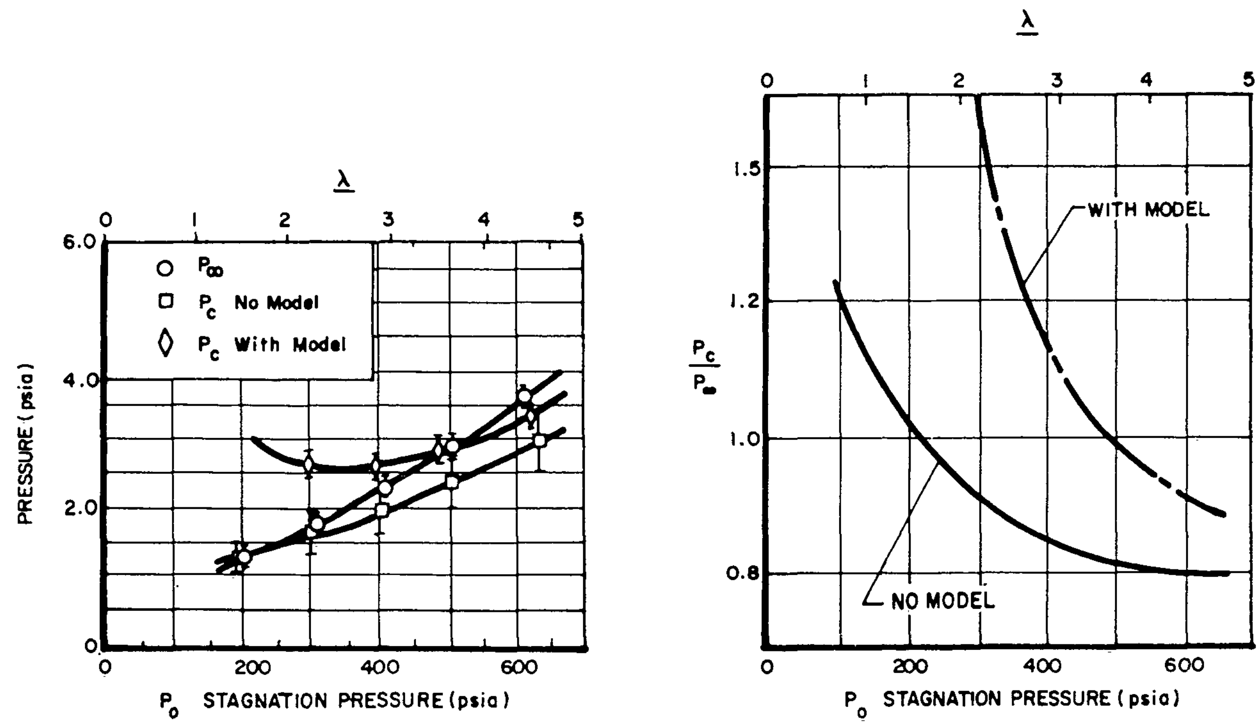


Figure 2. Effect of Model on the Test Cabin Static Pressure, with Plenum Pumping

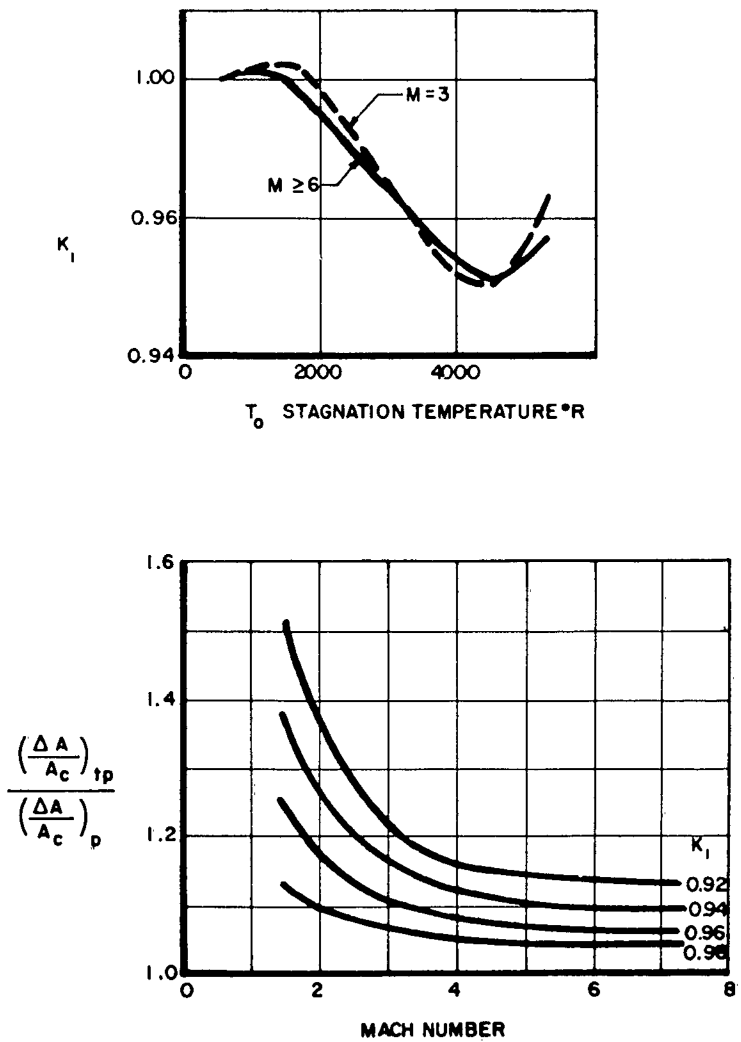


Figure 3. Effect of Caloric Imperfection on the Maximum Model Size Based on One-Dimensional Normal Shock Theory

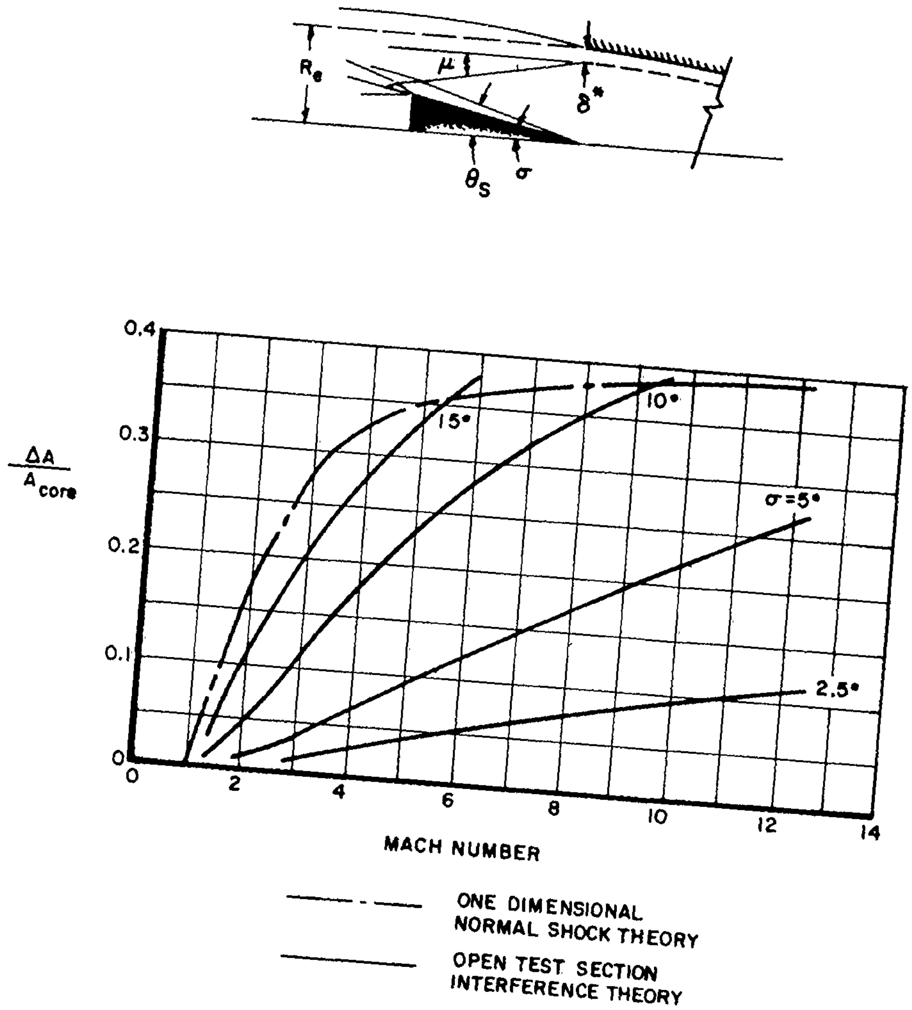


Figure 4. Theoretical Maximum Model Sizes for Open and Closed Test Section Configurations

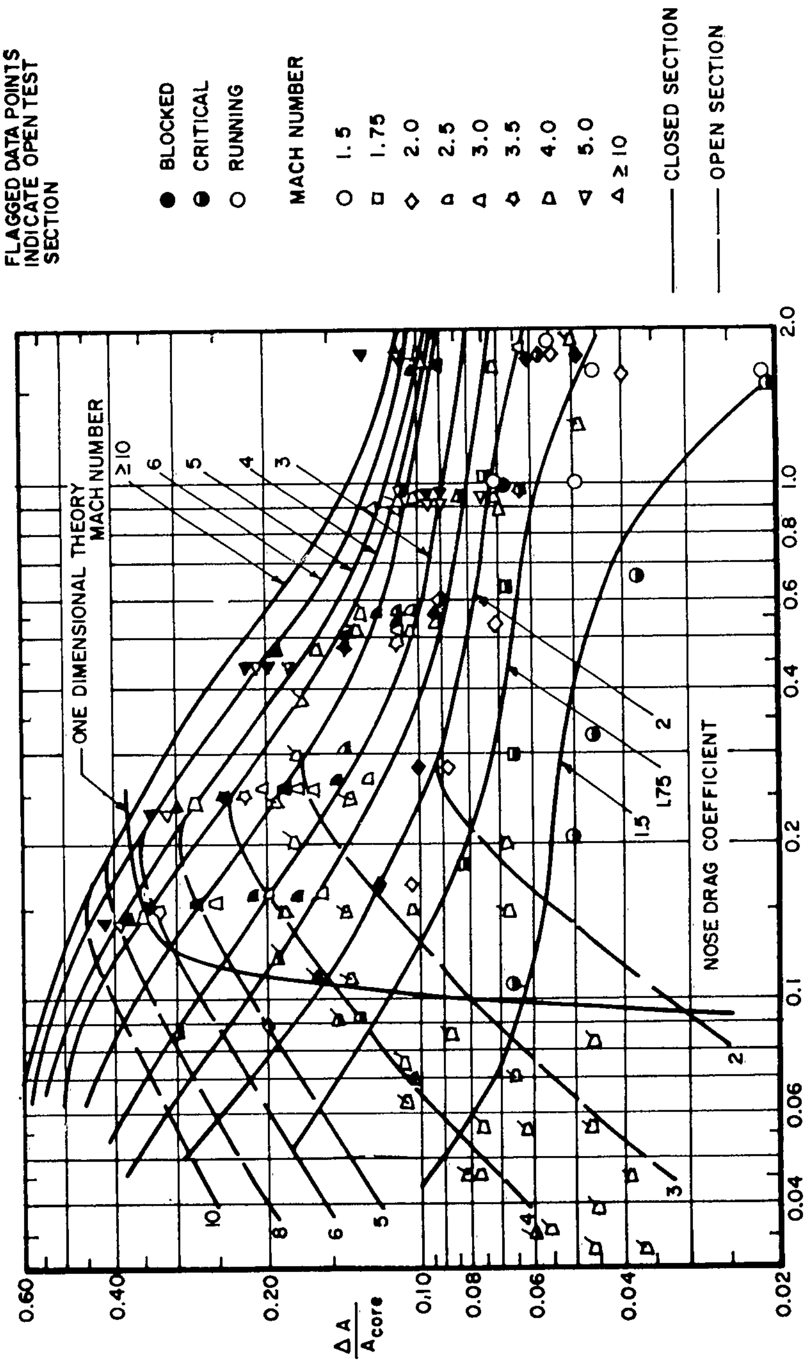


Figure 5. Correlation of Blockage Data for Closed and Open Test Sections

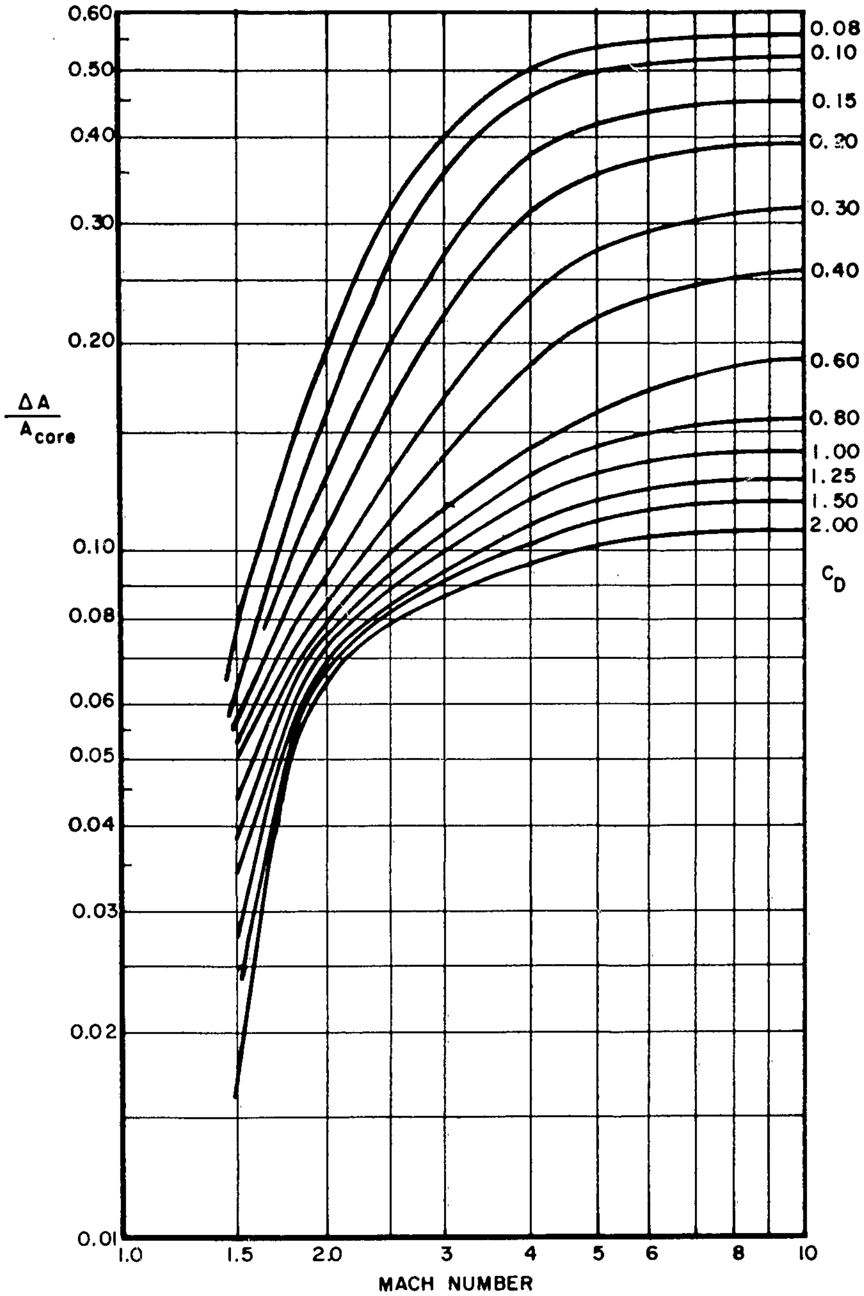


Figure 6. Permissible Model Frontal Area for Closed Test Sections as a Function of Mach Number and Drag Coefficient

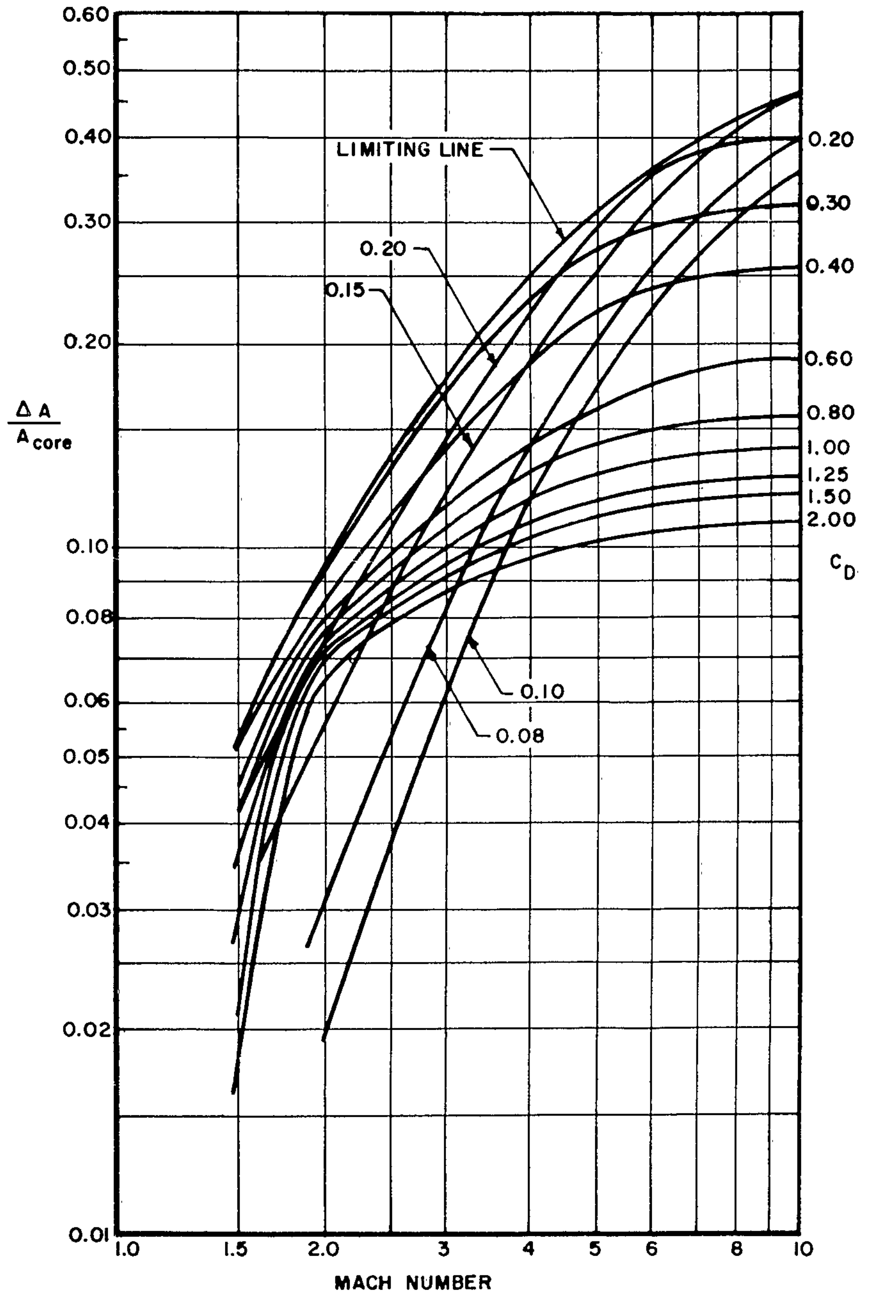


Figure 7. Permissible Model Frontal Area for Open Test Sections as a Function of Mach Number and Drag Coefficient

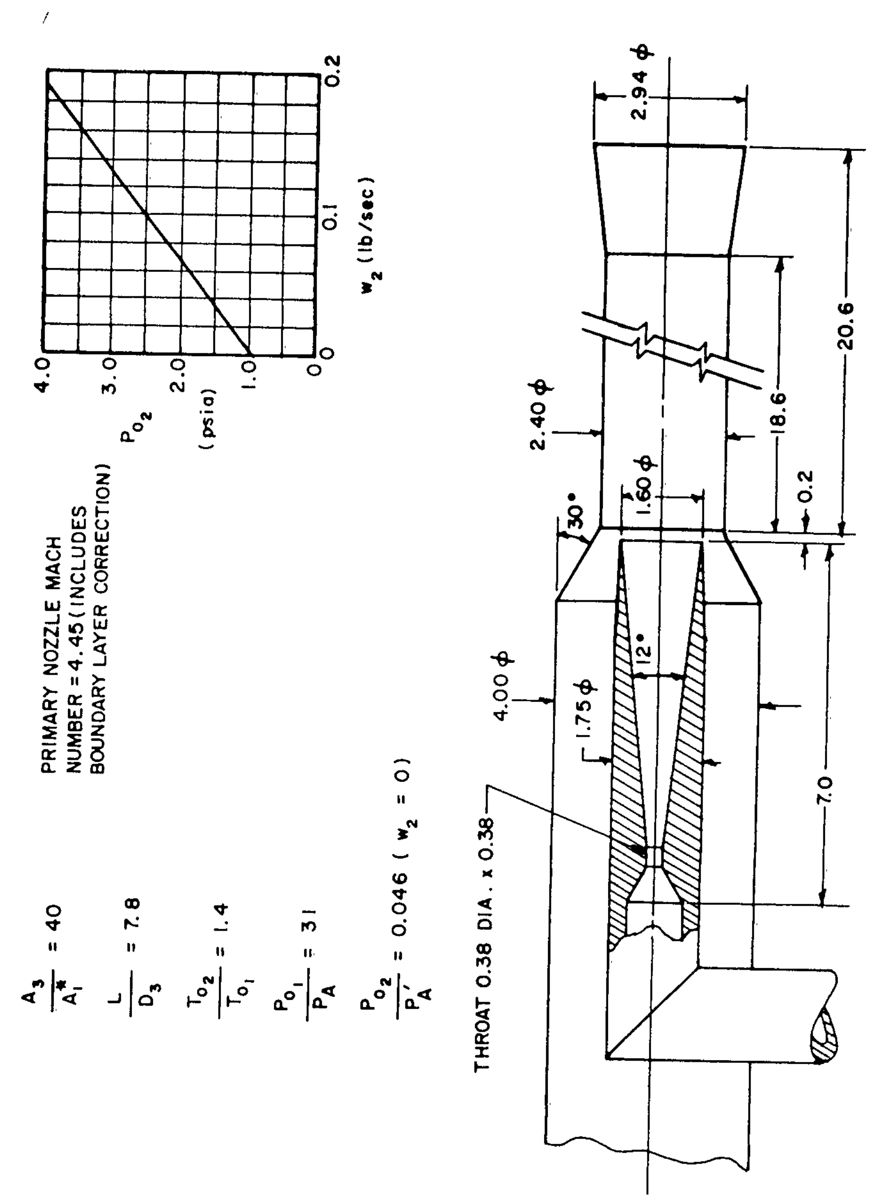


Figure 8. Ejector Configuration and Performance for Plenum Pumping of HTF Facility

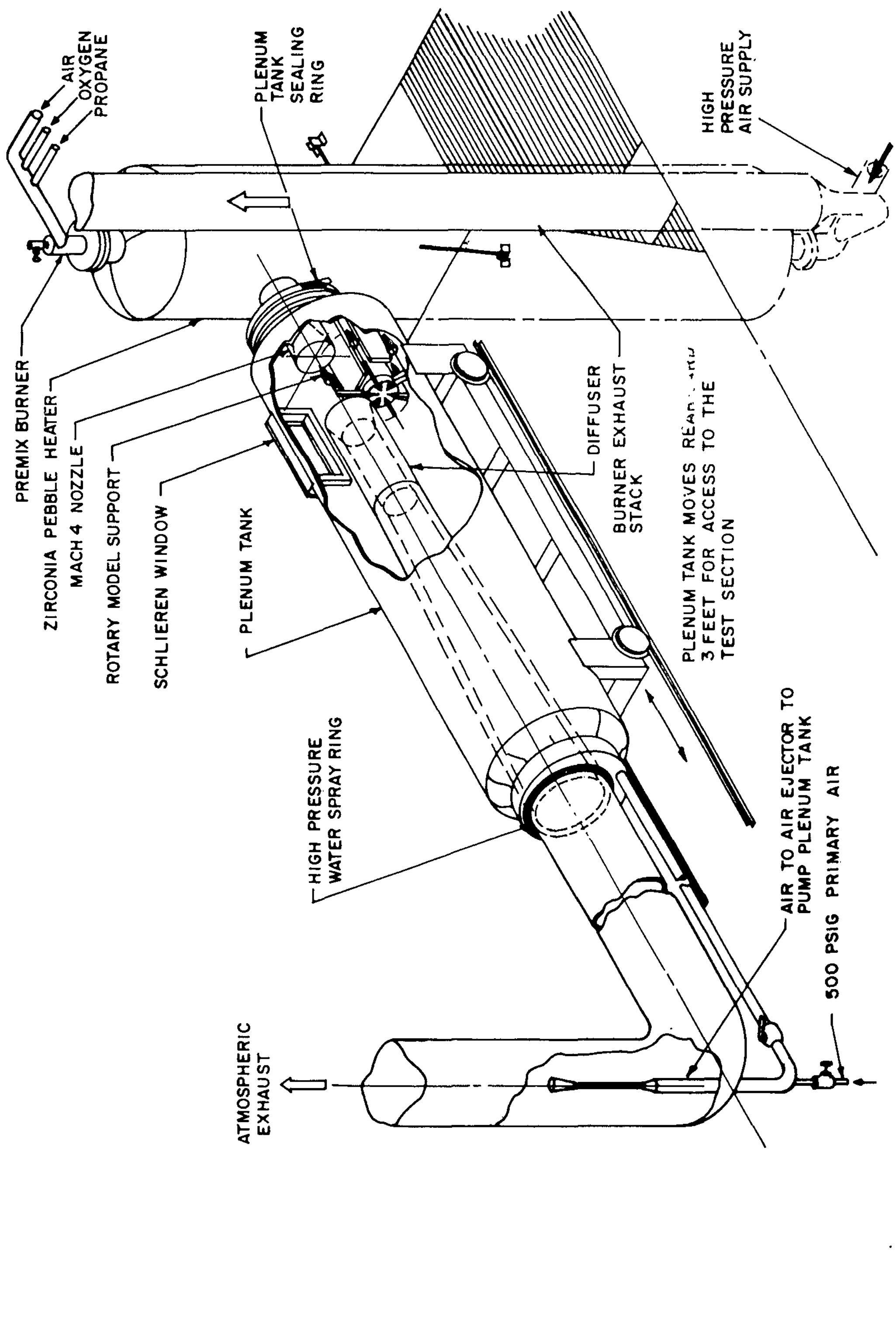


Figure 9. High Temperature Facility General Arrangement

RUNNING

$T_0 = 3500°R$

$P_0 = 315$ psia

$M_\infty = 4.00$

$\frac{\Delta A}{A_{core}} = 0.0682$

BLOCKED

$T_0 = 3500°R$

$P_0 = 253$ psia

$M_\infty = 3.99$

$\frac{\Delta A}{A_{core}} = 0.0688$

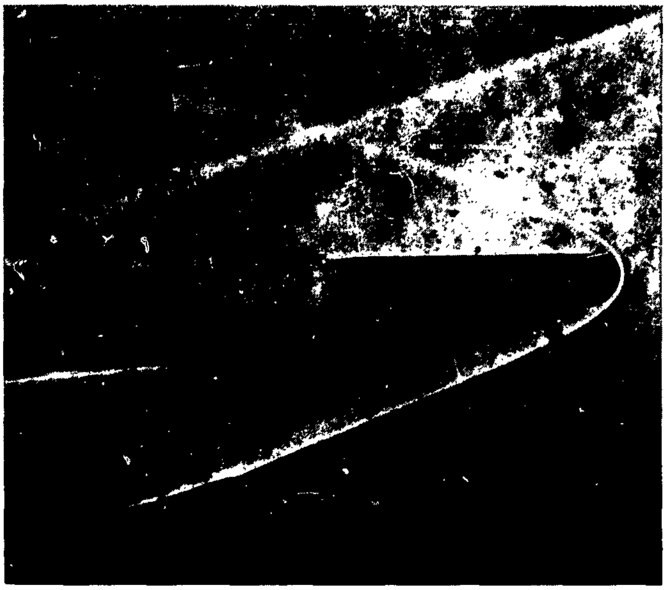
Figure 10. Schlieren Photographs of Typical Models

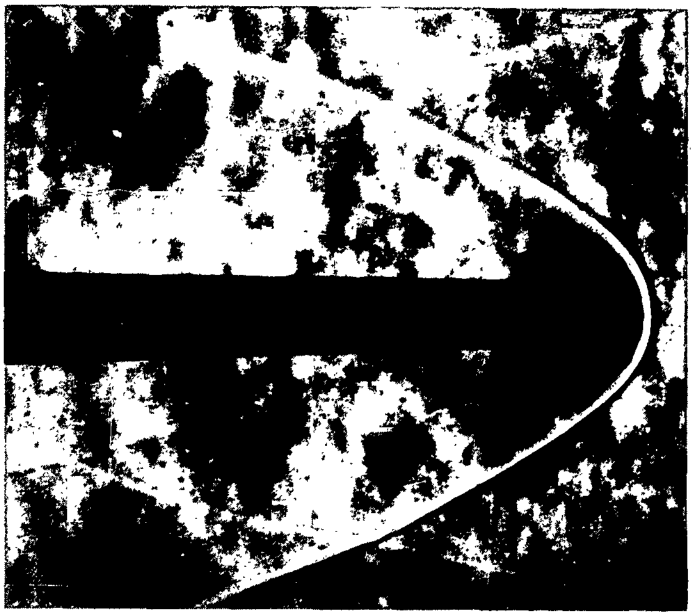
15° HALF-CONE

T_0 = 3000 °R

P_0 = 515 psia

M_∞ = 4.29





HEMISPHERE-CYLINDER

T_0 = 4200 °R

P_0 = 311 psia

M_∞ = 3.93

Figure 10. (Cont'd) Schlieren Photographs of Typical Models

10° HALF-ANGLE CONE

P_0 = 615 psia

T_0 = 3100 °R

M_∞ = 4.29

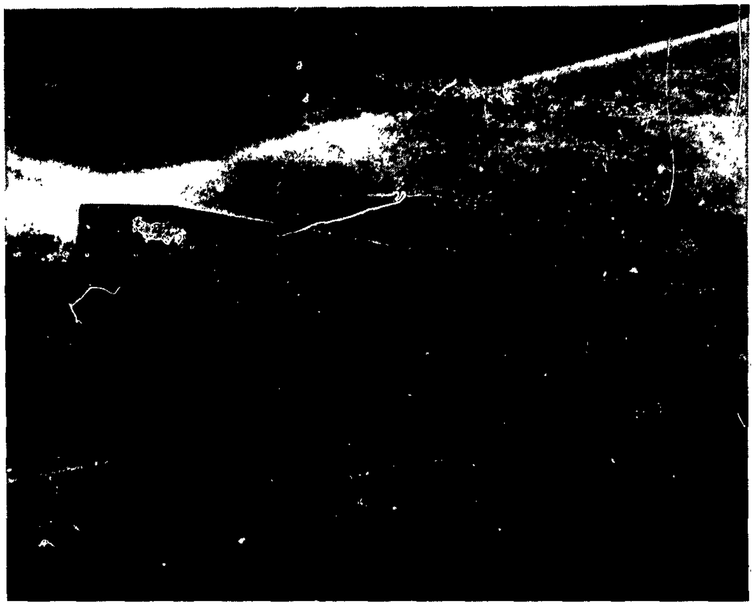
Figure 10. (Cont'd) Schlieren Photographs of Typical Models

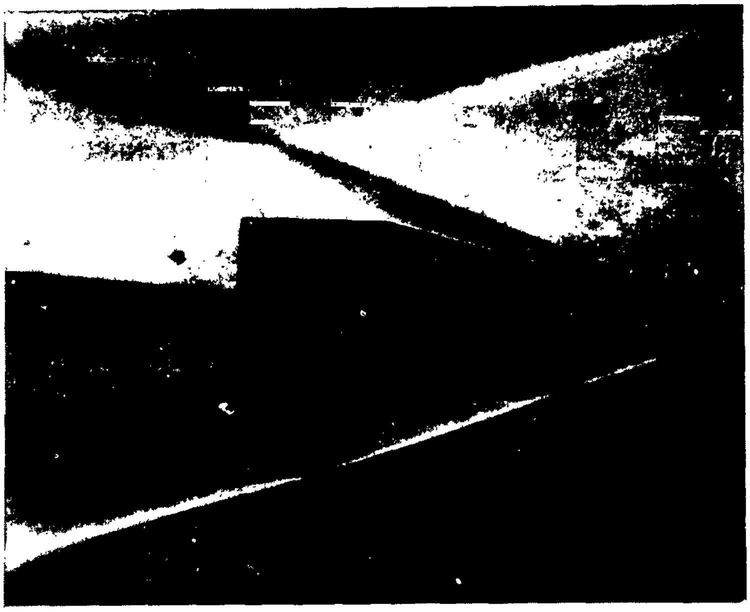
10° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3500 °R

M_∞ = 4.24





15° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3500 °R

M_∞ = 4.24

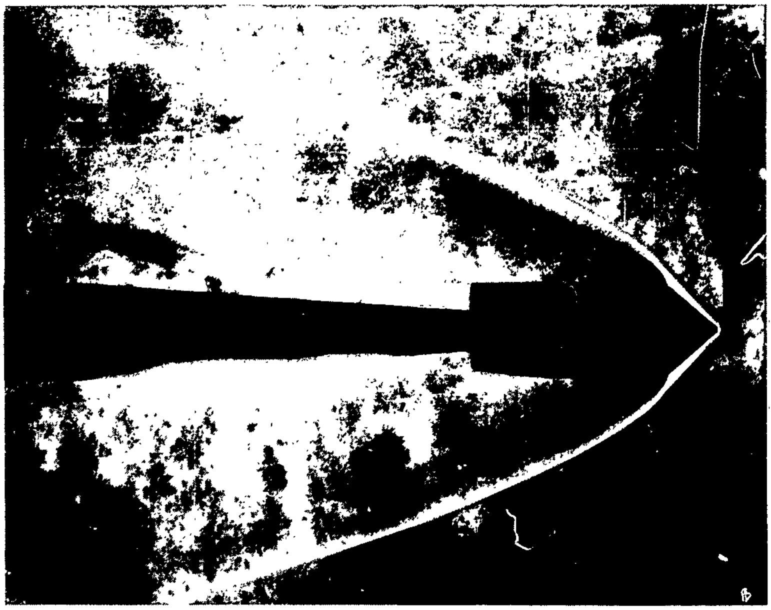
Figure 10. (Cont'd) Schlieren Photographs of Typical Models

20° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3570 °R

M_∞ = 4.20



40° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3570 °R

M_∞ = 4.20

Figure 10. (Cont'd) Schlieren Photographs of Typical Models

50° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3610 °R

M_∞ = 4.22

90° HALF ANGLE CONE

P_0 = 415 psia

T_0 = 3610 °R

M_∞ = 4.22

Figure 10. (Cont'd) Schlieren Photographs of Typical Models

Aeronautical Systems Division, Dir/Engineering Test, Aerodynamics Division, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-63-230. CORRELATION OF WIND TUNNEL BLOCKAGE DATA. Final report, Apr 63, 21pp. incl illus., 14 refs.
Unclassified Report

An experimental investigation of the test section flow blockage characteristics was conducted at Mach 4 in the High Temperature Hypersonic Gasdynamics Facility.

The models utilized in this program were pointed and blunted cones from 5-degree half angle to 90-degree half angle, flat plates, delta winged shapes, and hemi-

(over)

1. Model
2. Blockage
3. Wind Tunnel
4. Hypersonic
5. Correlation
I. AFSC Project 142601
   Task 1426
II. Paul A. Czysz
III. Aval fr OTS
IV. In ASTIA collection

spherical models, some of which were run up to 40-degree angle of attack. Comparison of the data with other facilities resulted in a correlation of the maximum model size compared to the potential flow core size with Mach number and drag coefficient for both open and closed test section configurations for Mach numbers from 1.5 to >10.

Aeronautical Systems Division, Dir/Engineering Test, Aerodynamics Division, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-63-230. CORRELATION OF WIND TUNNEL BLOCKAGE DATA. Final report, Apr 63, 21pp. incl illus., 14 refs.
Unclassified Report

An experimental investigation of the test section flow blockage characteristics was conducted at Mach 4 in the High Temperature Hypersonic Gasdynamics Facility.

The models utilized in this program were pointed and blunted cones from 5-degree half angle to 90-degree half angle, flat plates, delta winged shapes, and hemi-

(over)

1. Model
2. Blockage
3. Wind Tunnel
4. Hypersonic
5. Correlation
I. AFSC Project 142601
   Task 1426
II. Paul A. Czysz
III. Aval fr OTS
IV. In ASTIA collection

spherical models, some of which were run up to 40-degree angle of attack. Comparison of the data with other facilities resulted in a correlation of the maximum model size compared to the potential flow core size with Mach number and drag coefficient for both open and closed test section configurations for Mach numbers from 1.5 to >10.